Sea-Level Rise

A White Paper on the Measurements of Sea-Level Rise in New Jersey and A Perspective on the Implications for Management

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Coastal Hazard Management Plan
Office of Land and Water Planning
New Jersey Department of Environmental Protection
Summer, 1996

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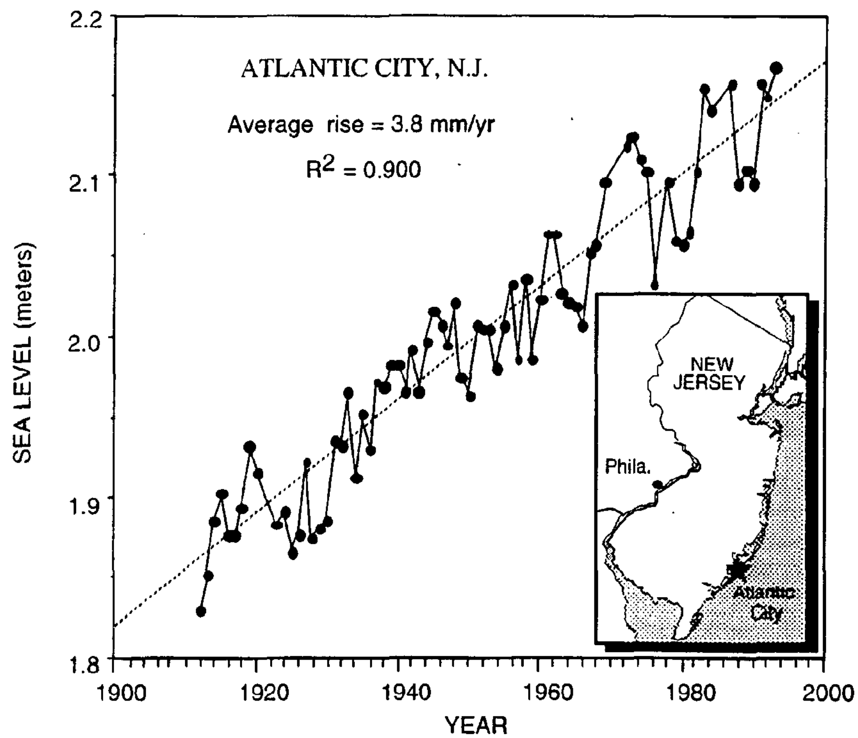

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Sea-Level Rise

The issue of sea-level rise has become a driving force behind coastal management strategies. The problem is not simply an increase of the water level against the land, but an increase of exposure to storm effects and an increase in the inundation and penetration of coastal storms acting upon higher water levels. Both international and national organizations have studied the rates of sea level rise on a global basis. The amount of sea-level rise along the New Jersey coast can be clearly identified through analysis of tide gage records. Its effects are manifested in a variety of changes that have occurred through the decades. As sea-level continues to rise, the coastal zone will be heavily impacted. This condition is further complicated by intense urban development that has occurred along much of our coastline. Therefore, it is incumbent that coastal decision-makers anticipate the effects of sea-level rise on the coastal zone and incorporate mitigation strategies which enhance public safety and reduce the exposure of the coastal zone from direct and indirect effects of sea-level rise.

Absolute and Relative Sea-Level Rise

Sea-level rise is composed of a combination of several factors. The most basic factor is the increase in the amount of water in the ocean. The melting of mountain glaciers and snow fields, along with a general expansion of the ocean as it warms, cause the ocean's surface to become elevated. This change in the amount of water in the oceans is referred to as the eustatic effect, or the absolute elevation of the water surface. A second factor of sea-level rise is that the coastal zone is subsiding or slowly sinking. Referred to as the tectonic effect, this is a characteristic of the older coastal margins of continents. Further, the new sediments which comprise barrier islands undergo some compaction because of their thickness and weight. As these sediments compact, it causes the overall lowering of the surface. The total change of sea-level is caused by the combination of these three factors which produce a net displacement of the water against the land. This is the referred to as relative sea-level rise. In discussing relative sea-level rise, it doesn't matter whether the land is subsiding or whether the sea is rising. Relative sea-level is the measure of how fast the land is becoming inundated. It is a measure of how fast you are getting wet.

The Effects of Sea-Level Rise

The issue of sea-level rise is multifaceted because so many indirect effects are associated with it. The problem is not simply the increasing water level of the ocean, but sea-level rise is also related to the general displacement of the shoreline at all of the margins of the barrier islands, and on all of the bayside communities, including those on the mainland. Further, as sea-level rises, the effects of storm conditions are able to reach farther inland. The smaller storms are able to reach levels and locations which were attained only by the rare event in the past. As sea-level rises, the effects of a diminishing sediment supply are also magnified. Whereas, the displacement of shoreline is perceived to be shoreline erosion, it is also a combination of elevated water levels as well. Therefore, an effect of sea-level rise is to contribute to the measurable displacement of the shoreline, and additional sand will be required just to maintain a constant position. Other issues include the change in the extent of and distribution of wetlands, habitats primarily in estuarine areas, the intrusion of saltwater into upper portions of estuaries, the salinity intrusion into groundwater, increased frequency of the inundation of evacuation routes, and effects on hazardous waste sites.

The Application of Sea-Level Rise Information

In the 1981 SPMP, the issue of sea-level rise was introduced as a variable that is changing the condition of the coast. Some general information was known and there was a record of water level changes that was observed in the tidal gages. However, there were few studies on sea-level change in New Jersey. Further, most of the discussion that occurred was theoretical and focused on the problems associated with future sea-level rise. A major advance in the investigation of this phenomenon occurred when additional information about sea-level rise became easily accessible. This influx of information has made it possible to describe long-term records of sea level change, immediate past conditions of sea level, place the two in perspective, and produce a more confident statement about the consideration of future rates.

Concern for sea-level rise and its effects has generated considerable activity on a worldwide basis. Some of this interest is driven by a recognition that global climatic change is causing many environmental responses. One of these is an elevation of the global sea level. Some of the early prognostications called for extreme changes [greater than 10 feet (3 m)] within a very short time scale (less than a decade). However, the newer forecasts for rates of sea-level rise have been lowered and the concern has partially shifted towards analyzing approaches to coastal management that incorporate the multiple aspects of sea-level rise.

There are two major sources of information on regional sea-level rise: 1). The United States Environmental Protection Agency (USEPA) and 2). the Intergovernmental Panel on Climatic Change (IPCC), created as a joint effort of the United Nations Environmental Programme and the World Meteorological Organization. Both sources have been attempting to address the issue by compiling information and analyzing the current state of knowledge.

USEPA

Among the first offerings of the USEPA was a comprehensive portrayal of the greenhouse effect on changes in sea level (Barth and Titus, 1984). This report included a methodology to identify and to predict the factors which influence sea level. The report also incorporated scenarios of coastal and estuarine changes produced by sea-level rise. The general approach was to consider a range of scenarios (Figure 1). The scenarios ranged from a low of 56.2 cm (22.1 in) to a high of 345 cm (135.8 in) above the sea level of 1980 by the year 2100. The mid-range figures spanned from a low of 144.4 cm (56.9 in) to a high of 216.6 cm (85.3 in) above 1980 sea level by the year 2100. These calculations only pertain to the eustatic rise of sea level; thus an adjustment to the figures should be made to incorporate local subsidence and compaction. In New Jersey, the total relative sea-level rise would increase by about another 24 cm (9.44 in) above 1980 sea level by the year 2100. This would now raise the extremely high scenario to 369 cm (145.2 in) above sea level of 1980 by 2100. The lowest scenario would also be increased, reaching 80 cm (31.9 in) above the sea level of 1980 by the year 2100. Of especial importance was the conclusion which stated although there is regional variation in the rates of sea-level rise, the evidence points to an existing eustatic rise of about 15 cm (5.9 in) for the past century and a higher rate for the next century (Barth and Titus, 1984).

US National Research Council

The Engineering and Technical System Commission of the National Research Council (1987) made an inquiry into sea-level rise because of the estimates produced by the USEPA, other NRC reports, and a number of international symposia. They found that sea-level rise was occurring and that it would continue into the future. However, they cautioned that the rates of future sea-level rise are uncertain although it is likely that the rate would increase over its current value. They, therefore, adopted the position of describing three scenarios of sea-level rise, 50 cm (low), 100 cm (middle), and 150 cm (high) by 2100. Local subsidence and compaction would cause the land to sink and add to the rate of inundation. It was agreed that sea-level rise was exacerbating shoreline erosion and that horizontal shore displacement was on the order of 100 times the vertical rise of the sea.

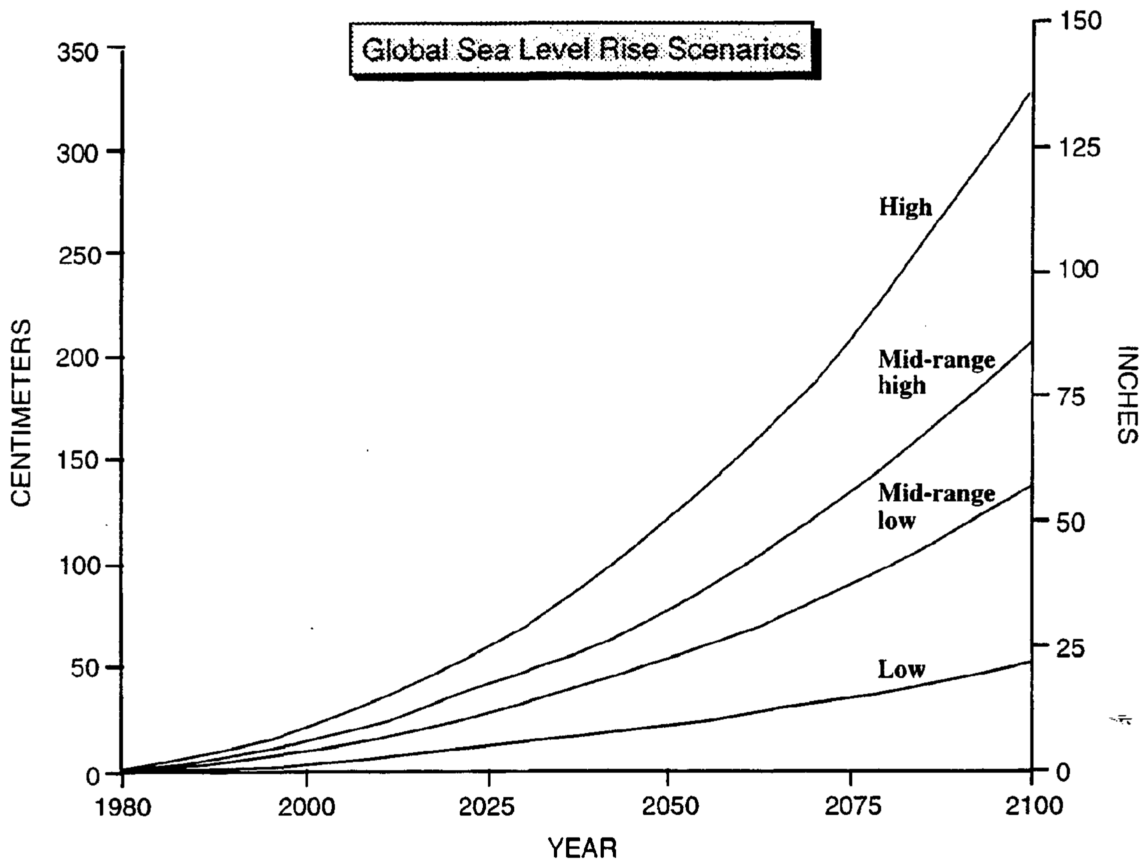

Figure 1. Source: Barth, M.C., Titus, J.G., 1984. Green House Effect and Sea Level Rise. Van Nostrand Reinhold Company, New York New York.
325 pages

Several other USEPA publications expanded on the sea-level rise theme by looking at the sort of environmental change effects produced in specific settings, such as the beach at Ocean City, Maryland (Titus, et al., 1985), salinities in Delaware Bay (Hull and Titus, 1986), and coastal wetlands (Titus, 1988). Much of the wetlands scenario development was based on the conditions presently occurring in coastal Louisiana where, because of the very large accumulations of the Mississippi River delta, the relative rate of sea-level rise in some areas is on the order 1.0 cm (.39 in) per year. Thus, the information about the effects of sea-level rise is based on empirical evidence. The outcomes of these studies and their extensions into places such as Delaware Bay and coastal New Jersey show that an increase in the rate of sea-level rise causes shoreline displacement, wetland loss, and drowning of the barrier islands. In other words, the effects of sea-level rise impact the entire barrier island and bay and wetlands complex.

Intergovernmental Panel on Climatic Change

Another source of information was and is being generated through the Intergovernmental Panel on Climatic Change. One of the thrusts of this panel was to concentrate on the effects of global climate change on the coastal zone. Several workshops were convened and information throughout the world was introduced to consider evidence regarding climate change, rates of change, effects of the change, and management options to deal with the present and future changes. As mentioned above, part of the investigation looked at changes in sea level. There was a large variation in the data assembled, and it was not possible to establish a single value of sea-level rise. Ranges of sea-level rise were developed (Figure 2), incorporating the concept of a high rate of rise value (110 cm or 43.3 in), a low value (31 cm or 12.2 in), and a best estimate (66 cm or 26 in) that applied to the period from 1990 to 2100 (Houghton, J.T. et al., 1991). Similar to the approach used by the USEPA, these values refer only to the absolute sea-level rise (eustatic). Also, similar to the products from the USEPA, the panel found evidence for a continuing elevation of sea level at present. At the moment, the IPCC is conducting research on the present rate of sea-level rise and its future rate. Thus far, they have concluded the rate is greater this century than last and will continue to increase in the next century. They are also sponsoring inquiry about the types of changes that may be expected at the shoreline and in the coastal habitats related to sea-level rise (Beukema, et al., 1990; Warrick, et al., 1993).

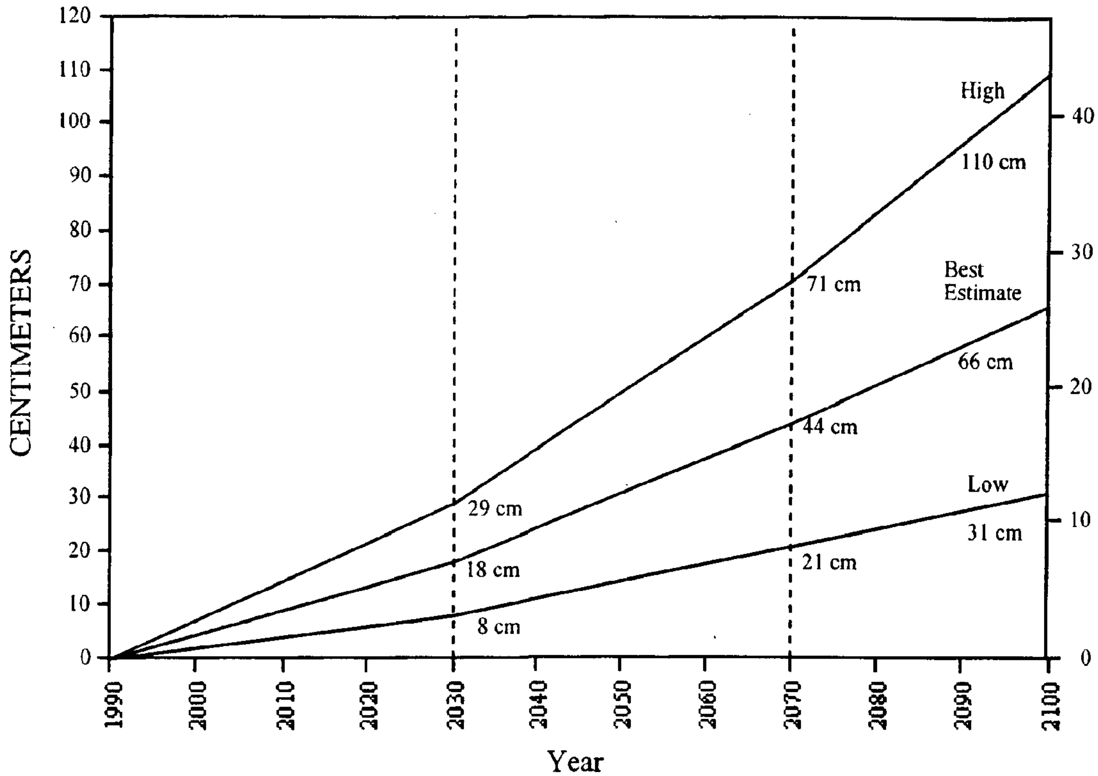

Figure 2. Global Sea Level Rise, Source: Houghton, J. T., G. J. Jenkins, and J. J. Ephraums (eds.). 1991 Climate change: IPCC Scientific Assessment, Cambridge University Press, Cambridge, UK, 362 pp.

Both the USEPA and the IPCC have modified their estimates of sea-level rise over the past several years. In general, the estimates have decreased slightly, primarily as a result of newer simulation models that reduce the contributions of the melting of the icecaps on Greenland and Antarctica to the world's ocean. Recently, the USEPA has released its latest view on the likely sea-level rise scenario to the year 2100. The approach was to poll a panel of experts on sea-level rise to consider the most probable rate on the basis of their responses. Increased rates of sea-level rise were paired with probabilities.

The results of the recent USEPA exercise applied to Atlantic City proceeds through a series of steps to produce a numerical value. The report concluded that the most probable outcome of sea-level rise is a 25 cm (9.8 in) increase from 1990 to 2100 above the existing trend for any area (Houghton, J.T. et al., 1991) (Table 1). Therefore, this number is added to the existing rate of relative sea-level rise to determine the future position. Data from gages in our local area provide the information on the existing rate (Table 2). The Atlantic City rate is 39 cm (15.3 in) per century. Thus, the most likely elevation of sea level in Atlantic City in 2100 would be 68 cm (25.6 in) higher than in 1990. Further, using the data in Table 1, there is a 10% change that the current rate would be exceeded by 55 cm (21.6 in) by 2100, providing a total increase of 97 cm (37 in) by the year 2100. Additionally, information from the table indicates there is a 1% chance that the additional rise could reach 92 cm (36.2 in) in addition to the current trend, raising total 2100 sea level to 134 cm (51.56 in) above the 1990 level. Once again the information points to a continuation of sea-level rise and a higher rate in the next century.

All of the scientific-technical agencies that have studied the question of sea-level rise have concluded that it is occurring and that it will increase in the future. The magnitude of the absolute rise is accompanied by the effects of local subsidence and compaction. Calculations of the impending inundation at Atlantic City created under the variety of scenarios from the different agencies portray the basis of a very serious problem for the low-lying coastal zone (Table 3). Even the smallest of these values would drive major changes to the system. And, these changes are occurring now.

NORMALIZED SEA LEVEL PROJECTIONS, COMPARED WITH 1990 LEVELS (cm)

Sea Level Projection by Year

Cumulative Probability (%)	2025	2050	2075	2100
10	-1	-1	0	1
20	1	3	6	10
30	3	6	10	16
40	4	8	14	20
50	5	10	17	25
60	6	13	21	30
70	8	15	24	36
80	9	18	29	44
90	12	23	37	55
95	14	27	43	66
97.5	17	31	50	78
99	19	38	57	92
Mean	5	11	18	27

Table 1. Source: Houghton, J.T., G.J. Jenkins, and J.J. Ephraums. (1991) Climate Change: The IPCC Scientific Assessment. Cambridge: University Press. pp. 362.

HISTORIC RATE OF SEA-LEVEL RISE AT VARIOUS LOCATIONS IN THE UNITED STATES
(mm/yr) (in/year)

Locations	(mm/yr)	(in/yr)
New York, NY	2.74	0.11
Sandy Hook, NJ	4.06	0.16
Atlantic City, NJ	3.85	0.15
Lewes, DE	3.11	0.122

Table 2. Source: NOAA, 1987-1994. Yearly Mean Sea Levels and Monthly Tidal Summary Reports for: Atlantic City, NJ; Battery, NY; Lewes, DE; Philadelphia, PA; and Sandy Hook, NJ. U.S. Dept of Commerce, National Ocean Service, Rockville, MD

ELEVATION OF SEA LEVEL AT ATLANTIC CITY UNDER VARIOUS SCENARIOS, INCORPORATING SUBSIDENCE
(elevation in centimeters, relative to 1990)

	Year 2000	Year 2025	Year 2050	Year 2100
EPA (1984)*				
Conservative	4.9	19.35	36.4	81.3
Mid-range , moderate	6.9	30.55	62.9	167.3
National Research Council (1987)*				
Low	7.1	25.2	43.1	78.6
Middle	11.2	39.4	67.6	123.8
IPCC (1990)*				
Conservative	4.5	15.5	32.0	58.5
Moderate	5.5	20.5	44.0	93.5
EPA (1995)*				
Best Estimate	5.0	18.7	33.5	68.1

Table 3. * Year of publication

Sea-Level Rise Rates in New Jersey

A number of studies have looked at the rate of sea-level rise in New Jersey. They have found sea level has been rising during the past several thousand years. Although these rates have fluctuated, they have continued to rise. An analysis of radio-carbon dates of organic materials accumulating in estuarine sediments has been reported by Psuty (1986) (Fig. 3). This study shows a general increase in sea level on the average of about 2.1 mm (0.08 in) per year until about 2500 years ago when the rise slowed to an average rate of about 0.8 mm (0.03 in) per year. The slower rate of rise was responsible for the last 2.0 m of inundation at the coast. It was during this time that a general stability of the coastal forms and habitats began to develop. However recent data from the local area indicate that sea-level rise is now occurring at a faster rate.

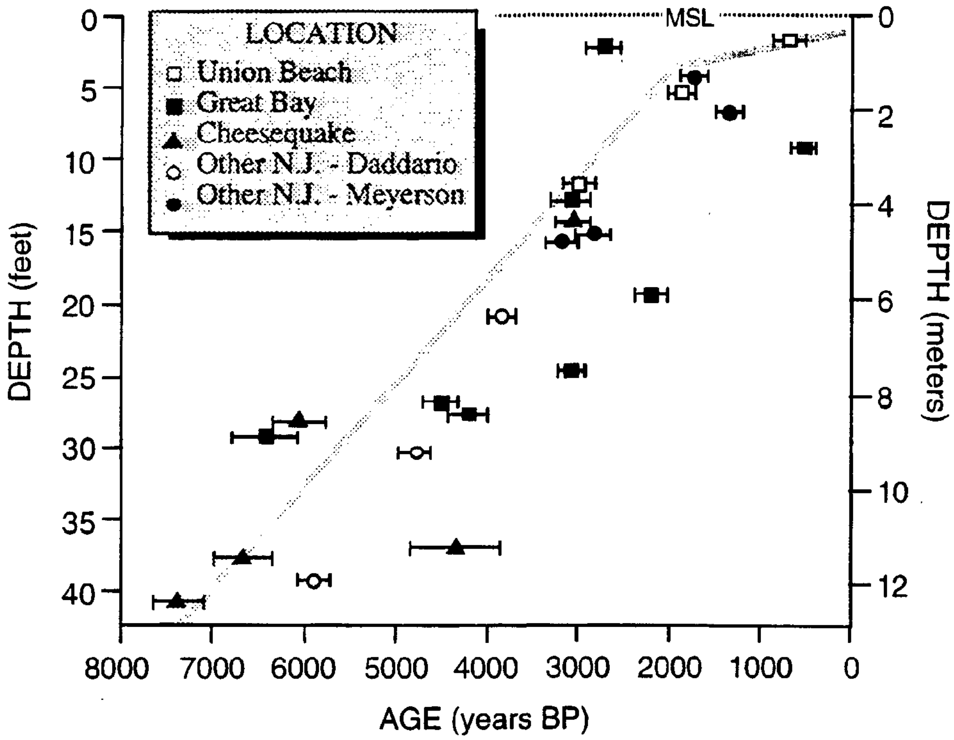

Figure 3. Trend of Recent Geologic Sea Level. The point on the scatter diagram are radio-carbon ages on materials taken from cores in New Jersey. The shaded line is the interpreted trend in elevation of sea level. The horizontal bars on the points represent the standard deviation in the age determination. Note the rapid rate of rise until 2500 Years BP and the ensuing slower rate of rise. (Psuty, 1986)

Tide Gage Measurements

Water levels measured by tide gages are the most convincing indication of the relative rise in sea level because they have produced long records of actual water level measurements. Since 1856, the tide gage at the Battery in New York City has recorded water levels. Figures 4, 5, 6, and 7 graph the yearly mean sea level against time from four tide gage locations in and near New Jersey. Specifically, these stations are: Battery, NY; Sandy Hook, NJ; Atlantic City, NJ; and Lewes, DE (Fig. 8).

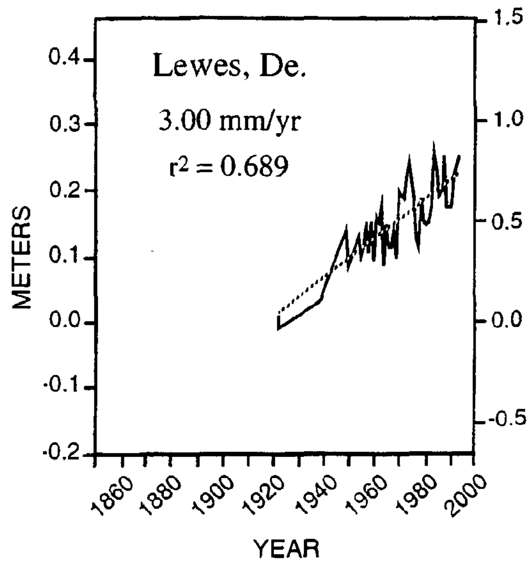

Figure 4. Yearly average sea levels for Lewes DE.

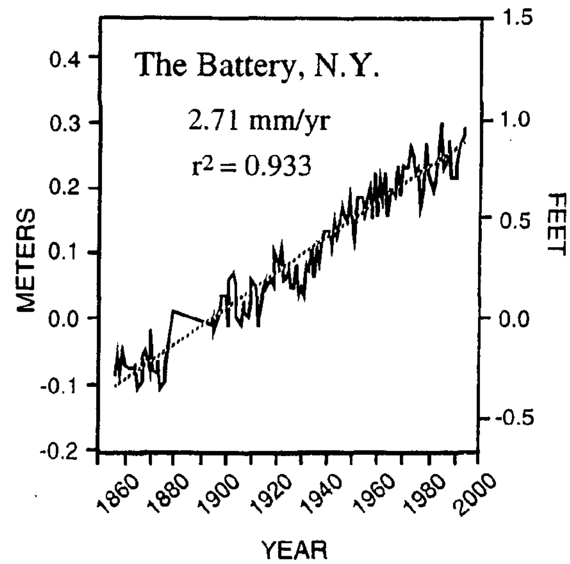

Figure 5. Yearly average sea levels for Battery N.Y.

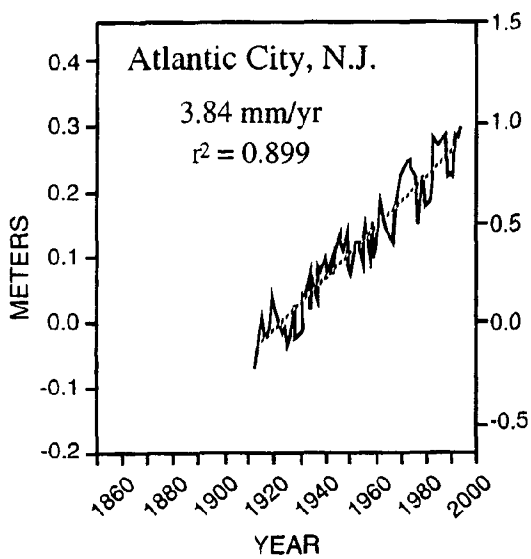

Figure 7. Yearly average sea levels for Atlantic City N.J.

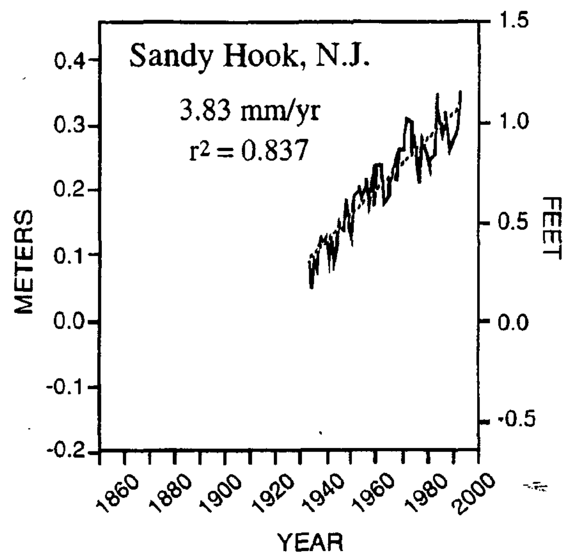

Figure 6. Yearly average sea levels for Sandy Hook N.J..

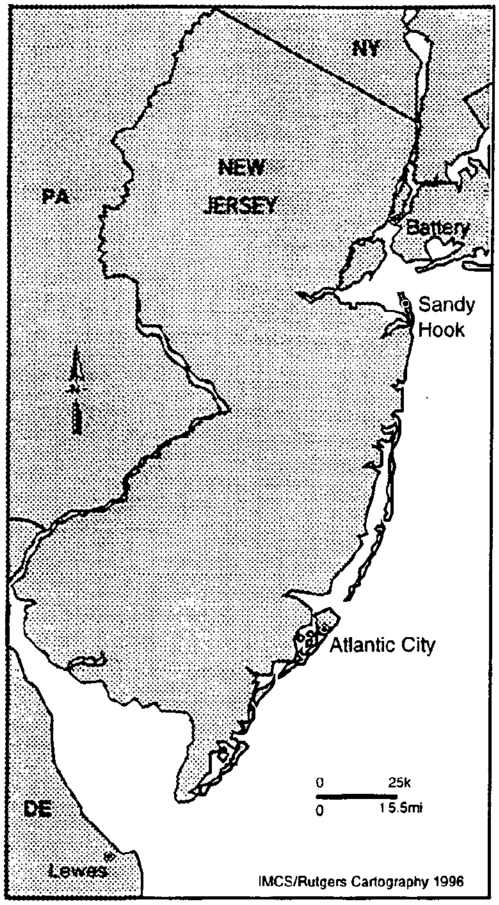

Figure 8. Location of Tidal Gauge Stations.

The value that is plotted for each year is the yearly mean sea level at a site relative to its datum. Each station has a somewhat different datum elevation, thus the absolute values of sea-level rise are slightly different. However, the relative values (the amount of increase per year, for example) are the important concern and they are available from these graphs. The yearly mean sea level is an average of the 12 monthly mean sea levels of that particular year. The monthly mean sea levels are an average of the measurements taken during that month. These graphs indicate and support an increase rate of sea-level rise. The graphs also indicate that the yearly mean sea levels vary from year to year. However, the fluctuations in yearly mean sea level are modest compared to the longer, upward trend (rise) that exists for each station (Figures 4, 5, 6, and 7). The average rate of relative sea-level rise varies between 4.06 mm (0.16 in) per year at Sandy Hook to 3.11 mm (0.12 in) per year at Lewes, Delaware (NOAA, 1994). The differing rates of rise are a result of the combination of the variables which affect relative sea level, especially subsidence and compaction.

In a report to the New Jersey Department of Transportation regarding sedimentation in Great Egg Harbor, Psuty, et al. (1993) looked at sedimentation rates on the Rainbow Islands in the bay. An analysis of $Cesium^{137}$ in the upper foot of peat and sediment accumulations on the islands shows a rate of rise of the marsh surface of about 6 mm/year (0.24 in/year) fro the past 30 years. This is higher than the averages for the tidal gauges during this century. The study probably demonstrates a greater rate of compaction of sediments in the estuarine embayments and indicates the wetland surface is being depressed at faster rates than the gauge locations on the barrier islands.

Extending the information presented in publications by the USEPA on Delaware Bay (Hull and Titus, 1986) and other areas (Beukema, et al., 1990), a report on the effects of a rising sea-level on New Jersey's coastal and estuarine areas was presented to the Governor's Science Advisory Panel (Psuty, 1991). This report proposed scenarios of environmental change into the future which are the products of different levels of sea-level rise (50cm, 100cm and 200cm). Topics included the amount of shoreline displacement, increased costs for shore protection, flooding of evacuation routes, greater frequency and magnitude of storm damage, salt water intrusion into ground water and wetland changes, The report stressed the changes in sea level that have and are occurring, and concluded that the coastal system is undergoing measurable. Psuty (1991) pointed out, although sea level may rise at a faster rate in the future, changes in sea level are occurring now and they will continue to occur.

The rate of sea-level rise at present is higher than any time in the past 7500 years (Fig. 9). It is very likely that the combination of sea-level rise and the paucity of sediment available in the system are causing adjustments in the coastal morphology and coastal habitats. Whereas the barrier island and wetlands were in adjustment with the slow rise of sea level of the past several thousand years, the faster rise is inducing disequilibrium conditions at the coast and in the estuaries. In the past 50 years, the undeveloped Rainbow Islands in Great Egg Harbor have lost about 5% of their area, one island has completely disappeared (Psuty, et al., 1993). As the still higher rates of sea-level rise develop, they will drive continual new adjustments and force new displacements in the coastal zone. However, it is the rate at which these wetlands are being submerged and it is largely responsible for the loss of wetland area on the Rainbow Islands.

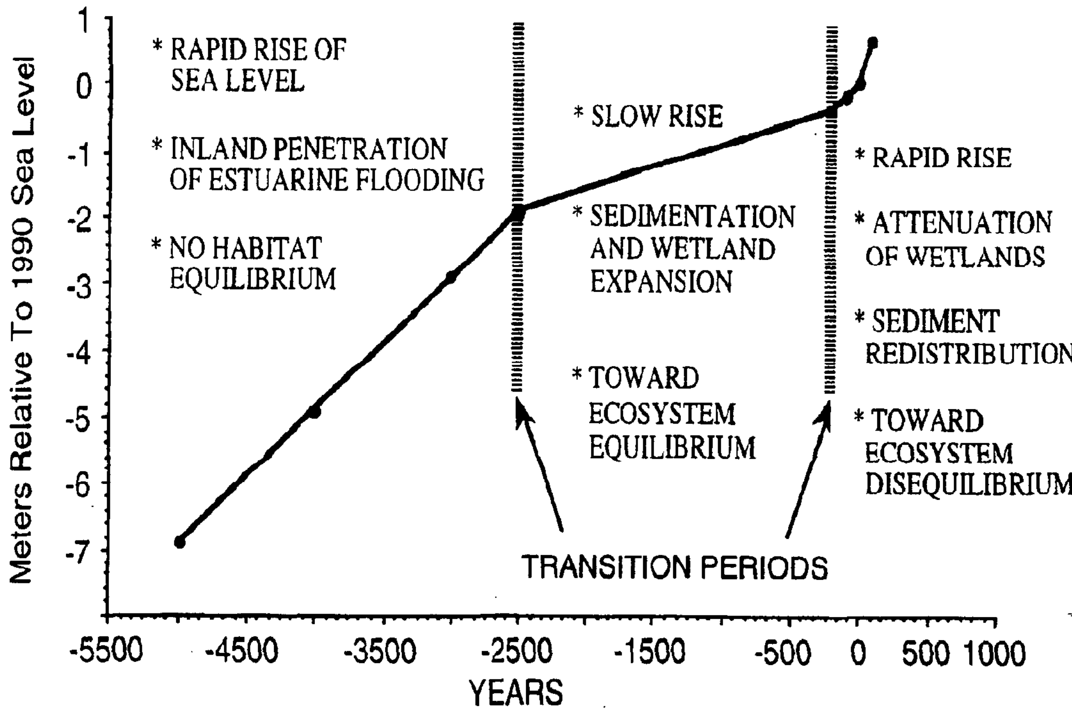

Figure 9. Coastal barrier islands and wetland development related to rate of sea-level rise. System disequilibrium is associated with high rates of rise (Psuty, 1992).

Application of Sea-Level Rise

Storm surge levels vary as a function of the storm's strength. However, there is another variable that determines the comparable level to which any storm can raise the water elevation and penetrate inland. That variable is the change in relative sea level through time. Sea level is rising. Therefore, the base upon which storms have occurred is changing. Thus, recent storms are now capable of reaching similar historical flood levels with lower surges. In addition, a rise in sea level allows stronger, less frequent events to reach coastal areas that where once safe from storm activity, exposing more areas to the erosional and flooding effects of a storm.

When comparing storms, it is possible to describe its surge level to a fixed datum, such as NGVD (Figure 10), or to a changing datum, such as sea level at the time of the storm. However, when comparing storms that are separated by several decades, some of the differences will be a product of sea level rise. For example, although Hurricane Gloria and the March 1962 storm were equal in water elevations reached [7.2 ft. (2.19m) above NGVD], Gloria operated on a sea level 0.276 ft. (0.07m) higher than the 1962 storm. Thus, because the March 1962 storm operated on a lower water base than Hurricane Gloria, the 1962 storm had a stronger storm surge than Hurricane Gloria in order to reach the same water levels.

Future Storm Levels**

Continuation of Previous Century's Rate

The impacts of sea-level rise through time are depicted in Figure 11 .Column A contains the water level elevations of the major storms that have reached New Jersey. Eleven storms are listed and portrayed according to their peak water levels above NGVD. In addition, the elevation of the water level is referenced to the FEMA frequency water levels. For example, the January 1987 storm is shown as having a storm peak water level of 5.9 ft and it is about a 1 in 5 year storm. This storm is labeled Number 2 and this storm and its number are incorporated in each of the other columns in Figure 11.

The left column is a compilation of the major storms of the past 52 years, including many of the post-1980 storm. In each case, the storm water elevation is the level achieved at the time of the storm relative to NGVD. This procedure does not identify the effects of sea-level rise during the period of record, although it is incorporated in the storm surge value. By way of example, the March 1962 storm had water levels equal to that of Hurricane Gloria in 1985, 7.2 ft. above NGVD. Yet, if those two storms were to occur in 1996, their comparative raised water levels would be different today because of sea-level rise. Their storm surges would be adjusted and raised at the rate of the past sea-level rise rate, 3.84 mm/yr (0.012 ft/yr). Thus, a storm equivalent to the March 1962 storm occurring in 1996 would produce a water level of 7.99 ft.(2.43m) above NGVD [compared to 7.2 ft.(2.2m) above 1962 NGVD] with an occurrence

** The predictions of future sea levels are discussed in Sea-Level Rise (Psuty, et.al., 1996), a Coastal Hazard Management Plan White Paper accompanying this report.

Comparison of Historic NGVD/MLLW Tidal Storm Surge Levels at Atlantic City

National Geodetic Vertical Datum (NGVD) (1929)	Mean Low Low Water (MLLW)
9.5'	11.1' **FEMA 100 Year Tidal Surge**
9.0'	
8.5'	10.1' **FEMA 50 Year Tidal Surge**
8.0'	
7.6'	9.2' Hurricane 1944
7.4'	9.0' December 1992
7.2'	8.8' March 1962, Hurricanes Belle, 1976 & Gloria, 1985, October 1991
7.0'	8.6' November 1950
6.8'	8.4' March 1984
6.3'	7.9' **FEMA 10 Year Tidal Surge** (*Margate Bridge Begins to Flood*)
6.0'	7.6' Hurricane Donna 1960
5.9'	7.5' January 1987
5.8'	7.4' **FEMA 5 year Surge**, January, 1992
5.3'	6.9' (*Black & White Horse Pike Begins to Flood)*
5.0'	
	.59' Minor Flooding (*average 6 times per year)*
0.59'	2.23 NOS Mean Sea Level

0.0' NGVD = 1.64' MLLW

Figure 10. A Comparison of Historic NGVD/MLLW Tidal Storm Surge Levels at Atlantic City. Source: State Hazard Mitigation Team, 1993.

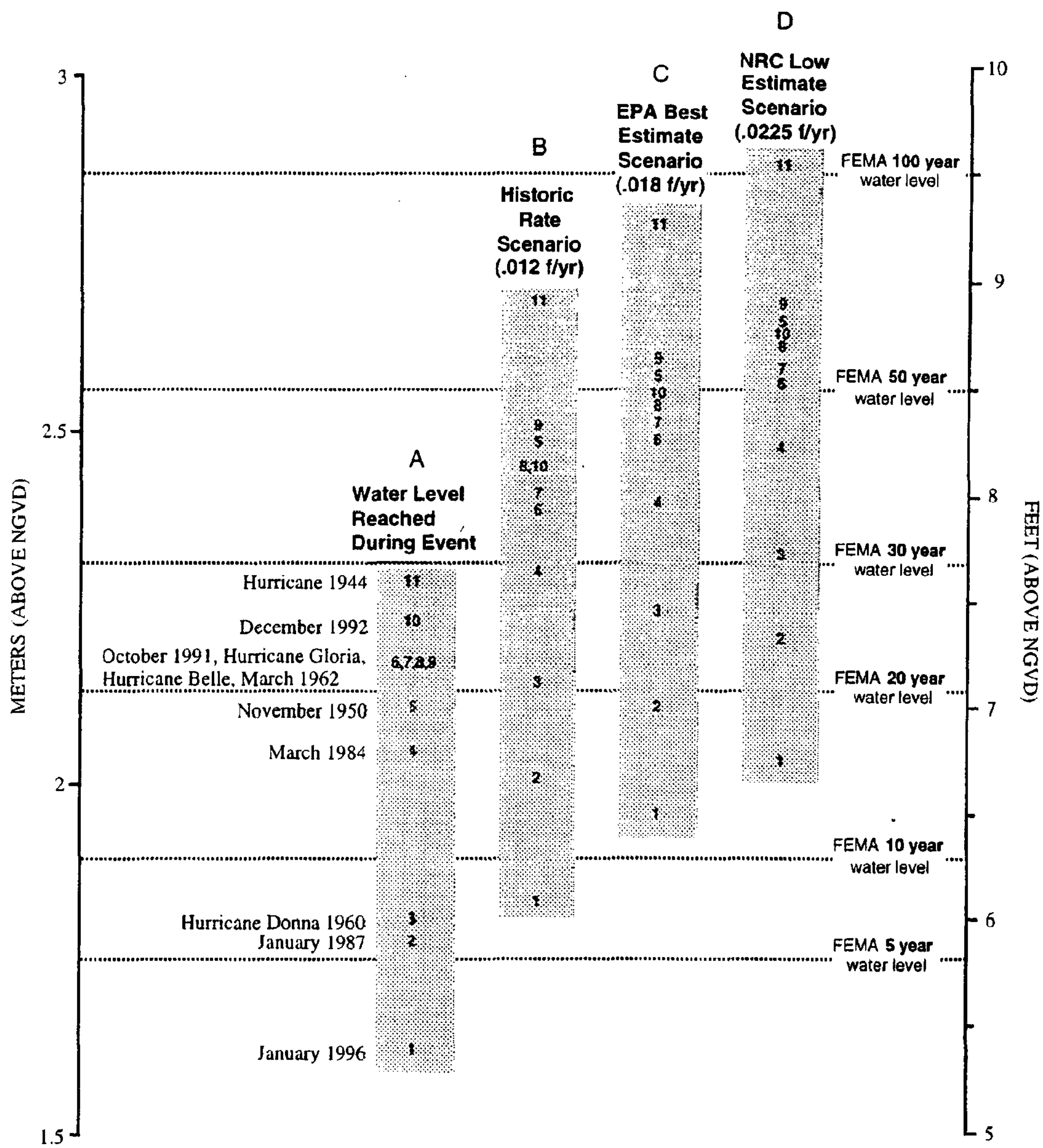

Figure 11. Projection of Historic Storm Water Levels to the Year 2050 Utilizing Three Predicted Sea-Level Rise Scenarios. Column A : actual level above NGVD. Column B: applying historic rate. Column C: applying Environmenat Protection Agency Best Estimate Rate. Column D: applying National Research Council Low Estimate Rate..

occur in 1996, water elevations would reach 7.33 ft.(2.24m) above NGVD Fig. 11B [compared to 7.2 ft.(2.2m) above NGVD in 1985]. In other words, if the 1962 storm were to occur today, it would surpass the flood levels of Hurricane Gloria, its water levels would be higher than the December 1992 storm, and its levels would even surpass the 1944 Hurricane.

Extending the effect of sea-level rise on future storms, Figure 11 projects the occurrence of past stormwater levels to their equivalents in the year 2050 and illustrates the difference between storm surges of the olderverse the more recent events. Applying the sea-level rise rate of 3.84 mm/yr. (0.012 ft/yr.) (Column B), an event similar to the December 1992 storm would produce a water level 8.13 ft. (2.48m) above NGVD in2050 or a 1 in 33 year storm. Similarly, if an event equivalent to Hurricane Gloria were to occur in 2050, expected water levels would be 8.02 ft. (2.44m) above NGVD. Further, if an event similar to the devastating 1962 storm were to occur in 2050, water levels could reach 8.31 ft. (2.53m) above NGVD, a 1 in 45 year water level.

If these past storm events were projected into the future using the U. S. Environmental Protection Agency's (EPA) "best estimate" sea-level rise rate of 0.018 ft./yr. to the year 2050 (Figure 11 Column C), the differences in water elevations reached can be further compared (Titus, 1995). Predicted water levels were determined by using the past century's rate of 3.84 mm/yr. until the year 1990, and EPA's rate from 1991-2050. Thus, the March 1962 equivalent storm would reach a water level 8.62 ft. (2.63m) above NGVD, a 1 in 60 year water level. An event similar to the December 1992 storm would reach 8.48 ft. (2.58m) above NGVD in 2050, a 1 in 50 year occurrence interval. If an event equivalent to Hurricane Gloria were to occur in 2050, the projected water level would be 8.34 ft. (2.53m) above NGVD.

National Research Council "Low Estimate" Rate

Estimated water elevations of similar events using the "low estimate" of accelerated sea-level rise (0.0225 ft./yr.) to the year 2050 from the National Research Council's (NRC) 1987 Responding to Changes in Sea Level report are also depicted in Figure 11 Column D. Predicted water levels were calculated by incorporating the past century's rate of 3.84 mm/yr. until the year 1990 and the NRC rate thereafter. Thus, if a storm event similar to Hurricane Gloria were to occur in 2050, using the NRC sea-level rise rate, projected water levels would be 8.61 ft. (2.62m) above NGVD. A similar storm to the December 1992 storm would be 8.75 ft. (2.66m) above NGVD with an equivalent occurrence interval of 1 in 65 years. Estimated water levels of an equivalent March 1962 storm in 2050 would be 8.89 ft. (2.70m) above NGVD, a recurrence interval of approximately 1 in 75 year storm. It should be noted the projected rates of relative sea-level rise used here are among the lower rates reported ~~in~~ literature. Other projected sea-level rise rates would result in higher elevations of storm water levels than illustrated in Figure 11.

One final comparison involves the 1994 Hurricane which produced a water level of 7.6 ft above NGVD when it occurred. This was the major storm and it retains that status throughout the several comparisons. Adding the projected sea-level rise to the year 2050 in the National Research Council "low estimate" scenarios produces an elevation of 9.53' NGVD, or greater than the 1 in 100 year flood in present day terms. The different between the 1 in 30 year flood level of its occurrence and the 1 in 100 year level is simply the effects of sea-level rise.

General Options for Management

Coastal storms will continue to occur and to inundate the New Jersey shoreline. These storms often result in the loss of life, extensive damage to property, and coastal erosion (Plates 4, 5, and 6). As sea level continues to rise, the effects of storms will be felt farther inland and across more of the coast. Efforts need to be taken to minimize potential losses from less frequent severe storms, as well as frequent low magnitude storms. Several issues must be considered prior to implementing any management strategies:

- Identification of high hazard areas.
- Identification, on a reach basis, of the level of protection from coastal storms desired.
- Creation of goals and objectives to be achieved in the year 2050, taking into consideration rising water levels.

As sea level continues to rise, most effects of coastal storms will be manifested initially and to the greatest extent in coastal areas prone to the erosional and flooding effects of storms. These high hazard areas need to be identified. Elevated storm water levels will cause damage to inland areas currently at little risk from flooding. Thus, policy decisions need to be taken to prevent further loss of life and damage to property in known highly exposed and vulnerable coastal areas. Conversely, policy is needed to reduce the continuous community and state investments to repair and reconstruct structures in these exposed areas. Additionally, there is a need to introduce a measure of flexibility into the designation of land-use, building codes, and densities. Zoning and boundary lines need to be adjusted on a timely basis to reflect changing exposure and risk brought about by rising sea-level and coastal storms.

Coastal decision makers must determine, on a regional basis, the level of protection desired to alleviate the effects of the probabilistic occurrence of storm waters to barrier islands and bayside communities. Options to protect reaches against a 1 in 5 year storm water levels differ from strategies to protect reaches from a 1 in 50 year storm. Although, protection from a 1 in 5 year storm requires less immediate investment than a 1 in 50 year storm, providing protection from a 1 in 5 year storm will require continuous post-disaster clean-up and repairs. Conversely, to provide protection against a 1 in 50 year storm will prevent flooding from frequent less severe storms; however, it may require expensive structural solutions such as dikes and may not be economically feasible or realistic. However, some level of protection against storms must be afforded. Thus, an intermediate approach such as providing protection from a 1 in 20 year storm may be the most feasible option. By providing protection from a 1 in 20 year storm, communities will be protected from the effects of both moderately-severe less frequent storms and well as frequent storms.

In those coastal areas with low density development, it is possible to consider options that call for relocation of structures and shifting out of the low-lying or severely-eroded portions of the coast that are being affected by sea-level rise. However, in the densely-developed coastal locations, little space is available to relocate buildings and/or infrastructure.

Therefore three strategies may be employed to reduce the public's exposure to the encroaching sea:

- Utilize seawalls, beach nourishment, dikes, and other constructed barriers to prevent the rising water from penetrating inland and to defend the existing shoreline.
- Allow the shoreline to shift inland and accept the losses of property and infrastructure at the water's edge.
- Take intermediate action to delay the effects of a sea-level rise while testing other approaches to the problem, this may involve short-term structures or nourishment with dune creation, in conjunction with phased changes in land-use in the most exposed areas; incorporate a rising sea level in all development plans and coastal policies.

The IPCC looked at options that could be applied to coastal management in the face of sea-level rise. No new revelations were put forward. The options were to build dikes (similar to the Dutch approach), allow the natural system to function and move back from the rising water (most of the developing world), or perform some short-term holding action while a longer-term solution is sought (delaying the hard choices).

The Engineering and Technical System Commission of the National Research Council's report on sea-level rise (1987) suggested that only two management options were available: 1) to stabilize the coast or 2) to retreat. However, no single option was preferred because of the wide range of variation in sea-level rise curves and the need to gather site-specific data in working on a structural solution. They indicated that a structural solution was always possible but it might be too expensive to apply. The report concluded that the evidence for an accelerated sea-level rise into the next century was well established and that it and its effects should be incorporated into sound planning and design.

Considerations and Challenges for New Jersey

Whereas the structural or retreat approaches noted above represent the extreme positions and will each be selectively applied, the intermediate approach may be the most universal and generate the most acceptance. However, even the intermediate approach will require the development of state policy to seriously treat the broad ramifications of the effects of sea-level rise.

- Initially, the investment and/or reinvestment of public funds in the coastal zone in post-storm situations should require adaptation to rising sea levels.
- Funding incentives and disincentives should relate to state policy to defend the shoreline or to move out of designated high hazard areas.
- Public policy must be created to determine the goals for the State in keeping with a higher sea level and a modified coastal zone. What are the objectives to be achieved in 50 years as sea level rises and inundation and displacement occur?

- Risk reduction and mitigation of the effects of sea-level rise relative to public safety and exposure to hazards must become part of public policy that manages the shore.
- There must be a recognition that the coastal system is highly dynamic and any means to interact with a changing system must be dynamic also. This especially applies to construction lines and land-use boundaries on maps and planning documents. The lines and zones must be revisited and revised periodically, particularly after major storm events.
- There must be the opportunity to change land use and distribution of facilities. There must be options to recreating the same land uses and structures, or the same densities as that which were damaged or destroyed previously.
- Strategies must be developed that lead to the achievement of the goals for coastal land use and hazard reduction.

The central issue raised in the discussion of sea-level rise and its increasing exposure of the people and infrastructure in the coastal zone is one of public safety and public protection. Retention of necessary waterfront development is also important. Whereas dikes will suffice in keeping the sea out, they can be an extremely expensive proposition. Other solutions are short-term and do not address the problem, merely delay facing the decision to make large public investments or to begin withdrawal from the most hazardous areas. Each of the choices is expensive. Each will require continuous investment as the coastal system changes. Any approach to addressing the effects of sea-level rise will require an allocation and expenditure of public funds. It is, therefore, paramount that these expenditures are led by a State policy that recognizes the need to respond to a changing situation and to have longer-term objectives that define what the shore is to look like in the coming decades. If changes are required, it is necessary to identify them and create the procedures by which they are incorporated in the planning process.

Nearly all of the management options discussed have focused on the effects of sea-level rise at the ocean shoreline. Accordingly, much of the discussion has also focused on approaches to defending the ocean shoreline. However, the effects of sea-level rise will be manifested on the shorelines of bays and estuaries in the coastal zone and they will likely be without the protective buffer of a beach and dunes. These locations are usually very low-lying initially and are very exposed to the effects of flooding. Much of the local infrastructure is near sea level at this time and will have increasing episodes of flooding as sea-level continues to rise. Therefore, the bay margins will need to be the first locations for the application of state policy development recognizing the effects of sea-level rise due to the high risks associated with sea-level rise.

Conclusion

Relative sea level in New Jersey has risen about 39 cm in the past century and will increase in the next century. The issue of sea level rise is a multifaceted phenomenon involving global and regional efforts. Yet these efforts have not established a single value of sea-level rise. Regardless of the rate that is considered, water levels are rising and the coastal zone is becoming inundated. The population and the development at the shore are at risk. The beaches have shifted and barrier islands have become narrower due to the displacement of the water-land contact. Low-lying bay shorelines are especially vulnerable as sea level rises. These risks will continue to increase in association with an increasing rate of rise. Thus, it is vital that coastal decision-makers anticipate the effects of sea-level rise on the coastal zone and develop policies that will enhance public safety and reduce the exposure of the coastal zone from direct and indirect effects of sea-level rise.

Although beach replenishment or construction of seawalls confront a portion of the problems associated with sea-level rise, neither can eliminate flooding or the high risk of damage from storms operating on elevated water levels. Policies are needed to direct the investment of public funds into projects that will enhance areas of adequate elevation to accommodate sea-level rise for some time period. Conversely, a policy is needed to reduce public expenditure for locations in high hazard areas that will require continuous repairs to both development and infrastructure. Further, there is a need to introduce a measure of flexibility into the designation of land use, building lines, and densities. Zones and boundary lines must be adjusted on some timely basis to reflect the changing exposure and risk brought about by a rising sea level.

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